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14. ABSTRACT

Practical approaches to modeling broadband acoustic propagation in range-dependent environments using normal mode theory were developed. A method for eliminating the branch line integral from the normal mode solution was developed, analyzed, and documented in a JASA article. The accuracy and characteristics of various adiabatic- and coupled-mode approaches for range-dependent benchmark problems were investigated. A method for extracting the acoustic modes of propagation and inverting for the acoustic parameters of the ocean and ocean bottom using data measured on a vertical line array was investigated. The results of the investigation were documented in a Ph.D. dissertation and in a JASA article.

15. SUBJECT TERMS

Underwater acoustics, normal mode modeling, geoacoustic inversion, vertical line array, mode extraction

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Broadband, Range-Dependent Normal Mode Modeling

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LONG-TERM GOAL

Our long-term goals are to develop practical approaches to modeling broadband acoustic propagation in range-dependent environments using normal mode theory, to improve the capabilities and efficiency of a specific acousto-elastic normal mode model (ORCA), and to provide support to others in the underwater acoustic community who use our modeling products.

OBJECTIVES

Work during FY98 focused on three areas: (1) developing, analyzing, and implementing a method for eliminating the branch line integral from the normal mode solution, (2) investigating the accuracy and characteristics of various adiabatic- and coupled-mode approaches for range-dependent benchmark problems, and (3) completing the documentation of work related to the ONR-sponsored Geoacoustic Inversion Workshop from the previous fiscal year.

APPROACH

The technical approach for eliminating the branch line integral from the normal mode solution was to replace the homogeneous halfspace with one that included an attenuation gradient and to find the modes that effectively replaced the Pekeris branch line integral. Evan Westwood and Robert Koch collaborated in this area. The adiabatic- and coupled-mode approaches have been analyzed by David Knobles and Robert Koch by applying them to the 1986 ASA benchmark problems. Documentation of the geoacoustic inversion results was performed primarily by David Knobles.

WORK COMPLETED

After arriving at the idea to insert a gradient into the lower halfspace in order to eliminate the branch line integral, we derived the reflection coefficient for such a halfspace and analytically studied the location of the modes in the complex k plane and the nature of their depth-dependent mode functions for the simplest case of a gradient halfspace below a pressure-release interface. A major part of the work was to implement the concept into the existing ORCA normal mode model,¹ which involved computing a different (non-zero) reflection coefficient for the lower halfspace, detecting whether a found mode belonged to the series of "branch line modes" (BLMs), finding the BLMs in the most efficient manner, and incorporating BLMs into the existing broadband algorithm. We presented three papers at the Seattle ICA/ASA meeting related to the subject²⁻⁴ and wrote a journal article for submission to JASA.⁵

The accuracy of the various adiabatic- and coupled-mode approaches was investigated by

implementing the theoretical formulations into computer programs and comparing the results to the benchmark solutions. Results were presented at the ICA/ASA^{3,4} and are summarized below.

Documentation of FY97 geoacoustic inversion work was completed and is to be published in Ref. 6.

RESULTS

The significance of the work on branch line modes is summarized below. The branch line integral is eliminated by replacing the homogeneous halfspace with one having a (complex) sound speed gradient. The branch line integral is replaced by a set of modes whose trajectory and spacing in the complex k plane depend on the magnitude and direction of the complex gradient. For a small, positive *sound speed* gradient, the branch line modes correspond to the former EJP branch cut. For a small, positive *attenuation* gradient, the branch line modes lie on a curve that leaves the former branch point vertically and that corresponds approximately to the former Pekeris branch cut. The total number of modes is minimized by the latter choice of gradient, in which case the modal spectrum consists of a finite number of trapped modes and infinite numbers of leaky and branch line modes. (The number of modes that are needed depends on the minimum range at which an accurate field is required.) Except when a mode lies near the former branch line, the trapped and leaky modes for a small-gradient halfspace correspond closely with those for a homogeneous halfspace. Larger gradients result in fewer branch line modes but larger errors (compared to the homogeneous halfspace) in the pressure field as range increases.

Modes for the gradient halfspace problem are found using the same method as that used in the ORCA normal mode model: the upward- and downward-looking reflection coefficients are computed at a reference depth, and the $R_1 R_2 = 1$ contour is followed in the complex k plane.¹ The usual trapped and leaky modes are found by placing the reference depth in the water column. The branch line modes, which appear as island modes for the usual choice of reference depth, are found on the main $R_1 R_2 = 1$ contour when the reference depth is set to the top of the lower halfspace.

Characteristics of the branch line modes, such as the frequency dependence of their eigenvalues, depth functions (see Fig. 1), and group velocities, have been examined in detail in Ref. 5. The behavior is consistent with the notion that the branch line modes represent the resonant behavior of the lateral wave component of the field: the eigenvalues of the branch line modes correspond to energy near the critical angle; their mode functions are large in the halfspace and peak up in the water column only when a trapped mode passes below them in the complex k plane [see Fig. 1(d)-(e)]; and their group velocities lie near the halfspace sound speed.

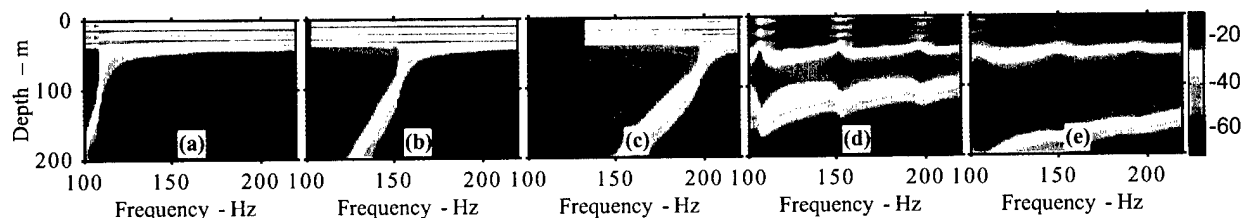


FIGURE 1. Mode function magnitudes in dB imaged versus depth and frequency for a Pekeris waveguide with an gradient halfspace: (a)–(c) modes 3–5, (d)–(e) branch line modes 1 and 2.

In Figs. 2 and 3, broadband calculations using gradient halfspaces are presented in both the frequency

and time domains. Figure 2(a) shows that, when a mode is near cutoff [in this case, mode 3 at 112 Hz – see Fig. 1(a)] the homogeneous halfspace TL is incorrect at all ranges and that the gradient halfspace corrects the problem. Figure 2(b) shows the error in TL between the gradient and homogeneous halfspace treatments versus range and frequency. The frequency interval over which the branch line modes are significant is about 3–5 Hz, and these intervals occur every 45 Hz (see Fig. 1). Figure 3 shows images of time series versus range for an environment (see inset) in which lateral waves are the primary mechanism of propagation. The inclusion of the branch line integral by way of the gradient halfspace in (a) produces the correct lateral wave behavior, whereas ignoring the branch line integral causes non-causal arrivals with lateral wave group speed in (b).

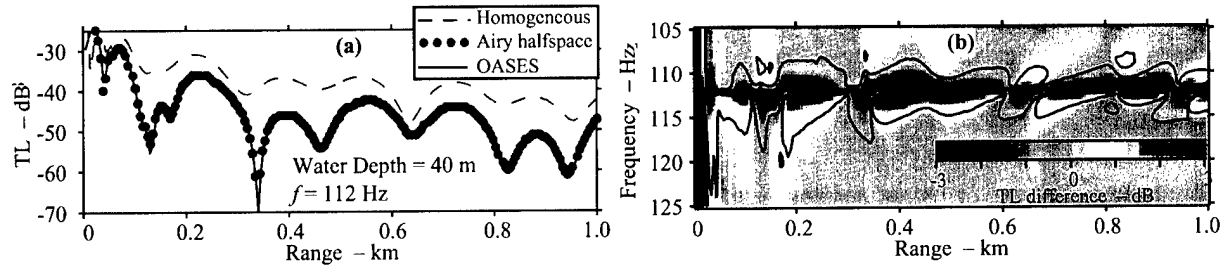


FIGURE 2. Transmission loss comparisons for a 40-m Pekeris waveguide. (a) TL versus range at 112-Hz; (b) TL differences between the gradient-halfspace and homogeneous-halfspace mode solutions.

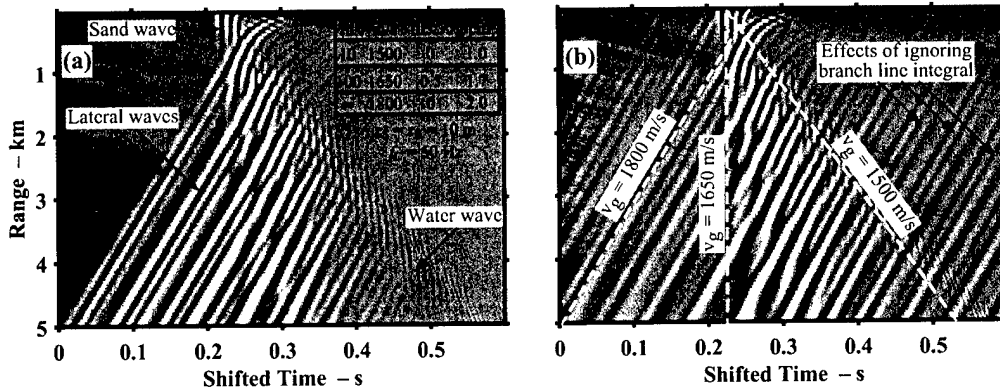


FIGURE 3. Normalized pressure time series versus range for a 50-Hz pulse in 10 m of water with a 100-m lossy sand bottom layer and a lossless lower halfspace: (a) using a gradient halfspace, and (b) using a homogeneous halfspace. Use of the gradient halfspace correctly accounts for the lateral wave energy.

The following lessons were learned from the work on adiabatic and coupled-mode calculations:

- Proper mode association (the pairing of modes from neighboring mode sets as one marches out in range) is critical for adiabatic, range-dependent calculations and is not straightforward when multiple ducts or branch line modes are present. For example, when a trapped mode moves past the branch point and becomes a leaky mode, its mode number, if given according to decreasing $\text{Re}(k)$, changes because it passes by the stationary branch line modes. Proper mode association in this case could be achieved by keeping the BLMs in a separate list. Modes can also change order when two or more ducts exist and a family of modes is trapped in each one. Improper association would result in energy trapped in one duct to suddenly jump into the another duct.
- Computing leaky modes constitutes an efficient method, compared to false-bottom techniques, for including energy that is steeper than the halfspace critical angle in normal mode calculations.

- Adiabatic TL calculations using trapped and leaky modes (TM+LM) are accurate for the lossy, penetrable-wedge ASA benchmark problem (using either a homogeneous or gradient halfspace). Although the *amplitude* of the field is correct, the *phase* of the field has a linearly-increasing error in depth, which is the difference between the adiabatic *vertical* modes and the adiabatic *wedge* modes (see Ref. 8 for more details on wedge modes).
- For the *lossless*, penetrable-wedge benchmark problem (using a homogeneous halfspace), the adiabatic TM+LM treatment exhibits errors because the modal transition from trapped-to-leaky is not smooth. When a gradient halfspace is used and the branch line modes are included, the results are much more accurate. (Here, proper mode association is required.) However, it appears that most of the accuracy gain is achieved by smoothing the trapped-leaky transition because even without the BLMs the accuracy of the gradient halfspace solution is good.
- A one-way, marching type of coupled-mode model⁹ using the TM+LM+BLM decomposition works well on the lossy wedge. Not only is the TL correct, but the phase is correct as well.
- A *two-way* adiabatic normal mode method based on the endpoint method is accurate for the pressure-release-bottom ASA benchmark wedge problem,¹⁰ which is demonstrated in Fig. 4, and correctly describes, *without coupling*, the significant backscatter.

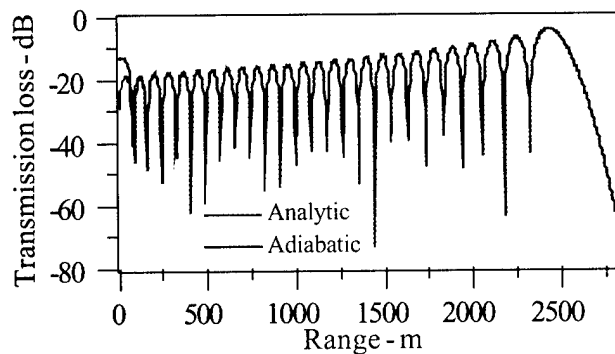


FIGURE 4. Comparison of two-way adiabatic mode results with analytic reference solution for 10-Hz version of ASA benchmark 1.¹⁰

- The adiabatic solution required in the differential form of the coupled-mode solution¹¹ may be replaced by the WKB form without loss of accuracy.⁴
- Perturbative expansion solutions (Lanczos series, Born series, and effective coupling operator) were obtained for sample ASA benchmarks and were found to converge to the exact coupled results.

IMPACT/APPLICATIONS

Most practical range-dependent acoustic propagation models are based on either the PE method or on normal mode theory. Reasons for continuing to pursue research in the area of normal mode theory include:

- Coupled-mode models, although currently too slow for most practical applications, can provide benchmark solutions to evaluate PE solutions, the accuracy of which can be sensitive to sampling and false bottom parameters.
- Adiabatic mode approaches are more efficient than PE when only a sparse set of source and receiver depths are required.
- In situations where mode coupling is important, the perturbative techniques mentioned above or wedge mode techniques may be viable methods for including first-order coupling effects in an efficient adiabatic approach.
- Normal mode theory provides quantities such as arrival times, multipath time spread, and vertical

arrival angles that are difficult to estimate using PE methods.

Regarding the research on eliminating the branch line integral, the gradient halfspace approach should also be useful for range-*dependent* normal mode calculations based on adiabatic or coupled-mode theory. Mode cutoff due to decreasing frequency is analogous to mode cutoff due to decreasing water depth, for example. Adiabatic treatment of the problem would be best achieved by keeping track of the branch line modes separately so that a trapped mode passing through cutoff transfers its energy to a leaky mode, rather than to a branch line mode. In reality, we would expect some degree of coupling at such a transition because the mode function of the trapped/leaky mode has a shape similar to those of the branch line modes. Another attractive aspect of the gradient halfspace approach for coupled-mode calculations is that the leaky modes eventually decay with depth, making the overlap integrals well defined. If the integrals can be solved analytically using Airy function identities, then the coupling calculations would be very efficient.

An important observation from our application of adiabatic- and coupled-mode theory to the ASA benchmark wedge problems is that an appropriate adiabatic treatment of those problems gives nearly exact results. Therefore we would recommend the development of a new set of benchmarks that would involve more complex range variability such that mode coupling was inherently important.

TRANSITIONS

Software and understanding gained under this work has continued to provide input into the enhancement of a broadband adiabatic mode model (NAUTILUS⁷) that is part of SPARS, a performance prediction tool developed for the Navy by ARL:UT.

We continue to make the ORCA normal mode model available to the community and to provide support to users when needed. We have been informed of use of the model at the following institutions: NRaD (Abawi's coupled mode calculations), MPL (part of genetic algorithm code SAGA); NAWC, U. of Hawaii (whale research); SACLANT (part of broadband, range-dependent code PROSIM; reverberations calculations); NRL SSC; U. of Victoria (ocean bottom parameter sensitivity studies); MIT/WHOI; University of Bochum (Germany); and Pennsylvania State University.

During the past year ORCA was used as a "mode engine" for a modeling tool that was developed by ARL:UT to provide range-dependent TL in real-world environments. The tool is part of a larger software package put together for the N87 program office for evaluating active sonar systems. Bathymetry and sound speed profiles for an area are obtained from the Web, the area is provinced, mode characteristics are computed, and adiabatic mode calculations are performed along radials.

RELATED PROJECTS

None.

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Geoacoustic Inversion Using Vertical Line Array Data

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LONG-TERM GOAL

The long-term goal of this work is to develop a method for inverting for the acoustic parameters of the ocean and ocean bottom using acoustic data measured on a vertical line array. Funding from this grant was also used to improve, maintain, and distribute a state-of-the-art acoustic normal mode model and to publish the results of previous work performed under ONR funding.

OBJECTIVES

The objectives of the FY99 work were to finish developing the software needed to perform the mode extraction and geoacoustic inversion, to conduct simulation studies of how the method is expected to work on real data, and to evaluate the practicality of the method by applying it to measured data.

APPROACH

The technical approach for the geoacoustic inversion method being investigated is (1) to use measured data on a vertical line array (VLA) to extract the depth-dependent mode functions of the environment, and (2) to invert for the environmental parameters by using a non-linear least squares technique for finding the best match between extracted and modeled mode functions. The approach for evaluating the usefulness of the method is to apply the method to the ACT II data measured in the Hudson Canyon area. This work is being carried out by Tracianne Neilsen as her Ph.D. dissertation topic in the Physics Department at the University of Texas at Austin, under the supervision of Evan Westwood. A more detailed description of the technical approach is given below.

The required experimental set-up for the mode extraction method consists of a source of opportunity moving in the vicinity of a VLA. The time-dependent, single-frequency pressure field measured on the VLA may be viewed as a matrix of pressures versus receiver depth and source-receiver range. A singular value decomposition (SVD) is performed on the pressure matrix. Under certain conditions, it may be shown, using the standard normal mode expression for the pressure field, that the resulting eigenvectors correspond to the depth-dependent normal mode functions of the waveguide. We refer to this procedure as mode extraction.

The experimental requirements for the mode extraction to work well are that the water column must be sampled sufficiently well by the receivers of the VLA and that the source must cover a sufficiently large range extent. These requirements allow the pressure matrix to be written as the product of three matrices that have the same properties as the matrices returned by the SVD. The first matrix has

orthonormal columns, which, if the extraction is successful, contain the depth-dependent mode functions. Modes that penetrate significantly into the bottom are not well sampled at the VLA, but this is not usually a problem in the far field because those modes suffer a larger amount of attenuation and are not strong enough to affect the extraction.

The elements of the third matrix of the SVD are proportional to $\exp(ik_n r_j)/\sqrt{r_j}$. To make these rows orthonormal, a range normalization is performed to remove the effects of geometric spreading. The remaining rows will be orthonormal if the elements of the sum over range of $\exp[i(k_n - k_m)r_j]$ fill out a circle in the complex plane. The number of rotations the elements of this sum make in the complex plane is $N_{\text{rot}} = (k_n - k_m)(R_{\text{max}} - R_{\text{min}})/2\pi$. The circle is most likely to be filled in if the number of rotations is large, or, equivalently, if the range extent $R_{\text{max}} - R_{\text{min}}$ is large.

Finally, the second matrix returned from the SVD is a real, diagonal matrix, whose elements are ordered from largest to smallest. The diagonal elements of this matrix are proportional to the modal source excitations. Thus the source depth chiefly determines the order in which the normal modes will be extracted. The main concern with the singular values is that when neighboring singular values are nearly equal, their corresponding singular vectors are not unique. In this case, the correct mode functions are linear combinations of the eigenvectors, which preserve the orthonormality condition. Modes having close singular values must be ignored in the inversion.

Once the mode functions have been extracted from the data, they may be used to invert for the parameters of the acoustic waveguide. The inversion method we used is based on Levenberg-Marquardt nonlinear optimization. In this method, the environmental parameters are adjusted to minimize the squared difference between the extracted mode functions and the corresponding mode functions modeled by the ORCA normal mode model.¹ Multiple frequencies are used in order to increase the amount of information contained in the inversion.

WORK COMPLETED

Software that performs the mode extraction and geoacoustic inversion was developed, and the entire procedure was tested using data simulated using the ORCA normal mode model and data measured during the ACT II experiment. Results have been presented to the underwater acoustics community at three Acoustic Society of America meetings.^{2,3,4}

RESULTS

Simulated data were generated to investigate the conditions under which the inversion may be expected to be successful. When the two orthonormality conditions, large range extent and good depth sampling, are satisfied, the mode extraction performs well. Further studies were performed to examine more realistic experimental conditions. It was found that:

- Random source phase has no ill effects on the mode extraction. This demonstrates that the method does not require controlled sources and that ships of opportunity can be used as sources.
- An SNR of at least 10 - 15 dB is needed to obtain consistently good mode extractions. Lower SNR tends to decrease the singular values, thus increasing the probability that the singular vectors will not be uniquely determined, as described above.
- When the array is tilted, the mode extraction process can tolerate a reasonable amount of tilt. Similar to other methods, the element locations need to be known to within $\lambda/10$ for good mode

extractions. A larger amount of tilt leads to the modes being flattened out. The higher frequencies are naturally most sensitive to array tilt.

The mode extraction technique was applied to data measured during the ACT II experiment. Fig. 1 shows the geometry of the ACT II VLA, one of the measured sound speed profiles, the bottom profile derived in the area from Ref. 5, and the mode functions for the waveguide at 150 Hz. The sparseness

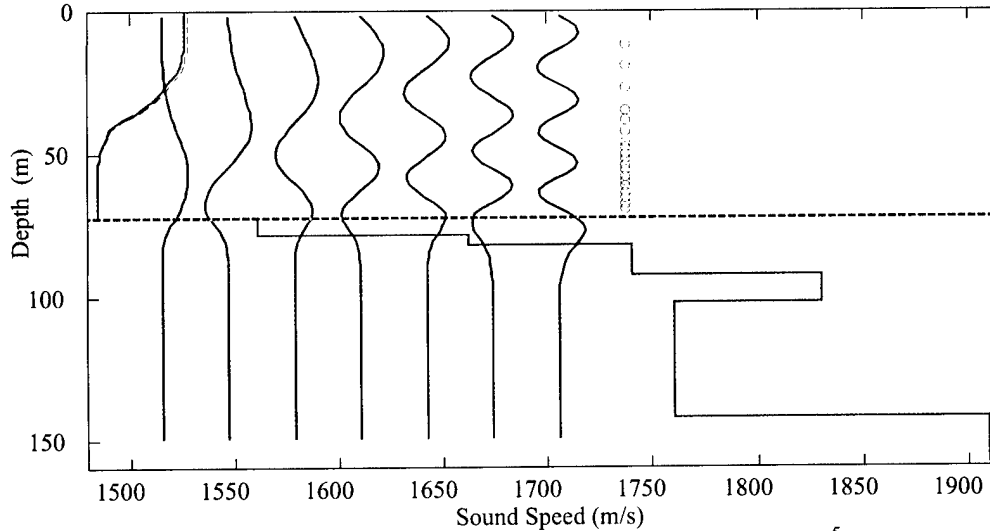


FIGURE 1. VLA elements (green circles), sound speed profile (red), nominal bottom profile⁵ (red), and mode functions (blue) for the ACT II experiment.

of the VLA in the upper part of the water column is not ideal, but simulations indicated that low-order modes could be extracted fairly well.

Mode extraction from the ACT II data was performed for various range extents for six tones from 100–500 Hz. The mode extraction worked better for the lower frequencies (100, 150 and 200 Hz) because the SVD eigenvalues were well separated and because the SNR was high. Extracted modes at 150 Hz for range-independent and range-dependent legs of the TL2/93 run are shown in Fig. 2. Both

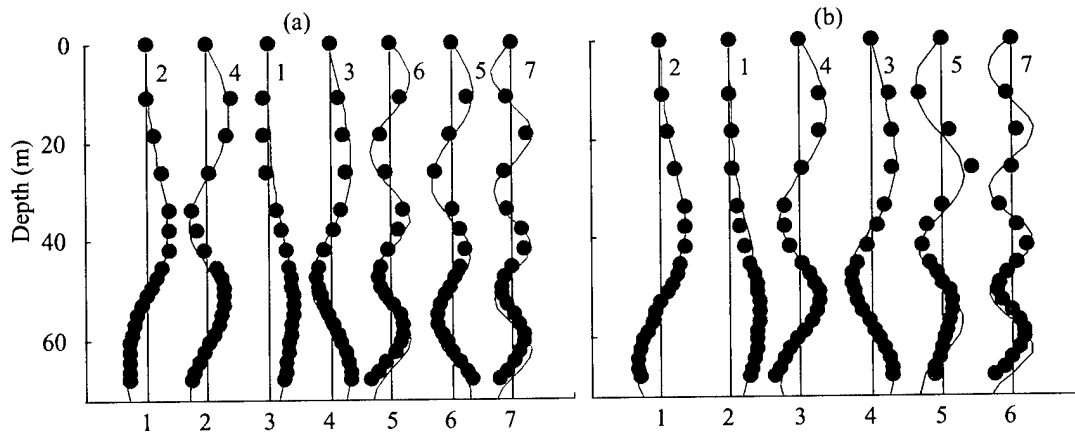


FIGURE 2. Extracted modes (circles) at 150 Hz from (a) a range-independent leg and (b) a range-dependent leg of the ACT II experiment using a range extent of 6–14 km. The continuous lines are modes modeled by ORCA for the nominal environment illustrated in Fig. 1.

extractions used range extents of 6–14 km. Despite the sparseness of the VLA, the mode extractions appear to have worked very well. The downward-refracting sound speed profile present during the measurements is reflected by the shapes of the extracted mode functions, particularly those of low order. The success of the range-dependent mode extraction indicates that, if the range dependence is small enough, the adiabatic approximation holds, the mode shapes adapt themselves to the varying water depth, and the modes are extracted as they exist at the VLA.

Next, the extracted mode functions were used to invert for the geoacoustic parameters of the bottom. The bottom was assumed to consist of two layers and a lower halfspace; the parameters allowed to vary were the layer thicknesses, the compressional-wave sound speeds and attenuations and their gradients, and the layer densities. The results of the inversion procedure are summarized in Fig. 3. The sound speed at the top of the first sediment layer is close to that given in Refs. 5 and 6. The result for the water depth agrees well with the value of 71.6 m derived in Ref. 7. The extracted modes are not sensitive enough to density or to any parameters in the second layer to give reasonable estimates of those values.

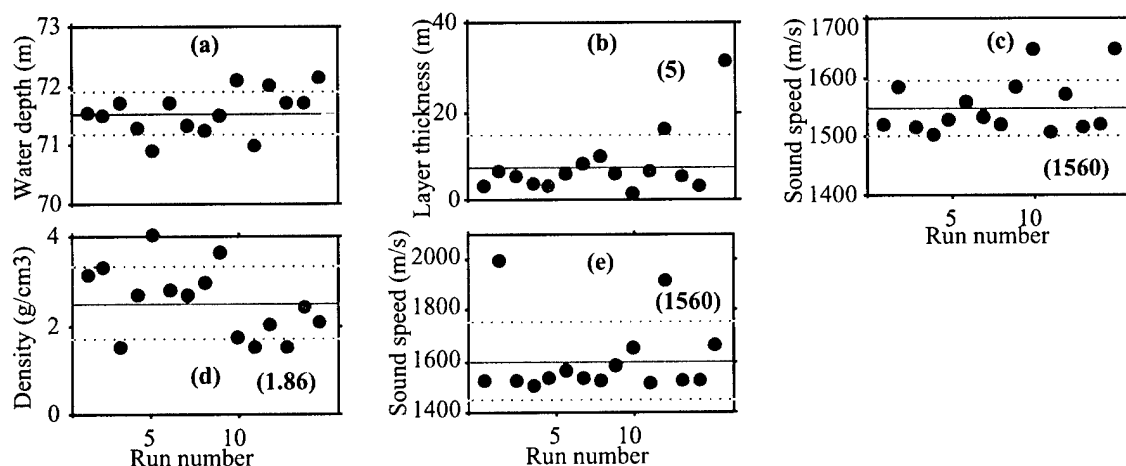


FIGURE 3. Inversion results using modes extracted at four frequencies from 200–500 Hz from a range-independent leg of the ACT II experiment. The three sets of colored dots indicate converged parameter values using sets of modes extracted from three different range extents. Within each color, five inversion runs were done using different starting environments. The mean value and standard deviation of each parameter for the 15 runs are also shown. The values reported in Ref. 5 are printed in bold.

In summary, theory and simulations indicate that the mode extraction technique should work well if the VLA samples the water column well, the source covers a sufficient range extent, and the SNR is good. The acoustic source need not be controlled: its depth, the phase of its tonals, and its precise track do not need to be known. When applied to the ACT II data set, the mode extraction appears to have worked very well, despite the relative sparseness of the array near the top of the water column. When the extracted modes were used to invert for the bottom, the results were encouraging, but the depth to which the parameter values could be reliably obtained was only 10 m or so. Since the mode functions decay rapidly with depth in the bottom, little information about the bottom below a few wavelengths is available. Although more information would be desirable, the field from sources beyond the near field is only dependent on the parameters near the surface. Unfortunately, the mode functions are not very sensitive to attenuation, even in the top sediment layer. The extracted depth-dependent mode functions are also useful for determining water depth and the sound speed profile in

the water column, but in practice these values can usually be measured by other means.

IMPACT/APPLICATIONS

This technique for geoacoustic inversion is applicable to vertical line arrays that span and sample the water column sufficiently well to account for the dominant modes of propagation. The source of acoustic energy must be quite loud and must traverse a sufficiently large range extent, but it does not have to be controlled, which makes it applicable to covert operations.

TRANSITIONS

No transitions have occurred for the geoacoustic inversion method. We continue to make the ORCA normal mode model available to the community and to provide support to users when needed. We have been informed of use of the model at the following institutions: NRaD, MPL; NAWC, U. of Hawaii; SACLANT; NRL SSC; U. of Victoria; MIT/WHOI; University of Bochum (Germany); and Pennsylvania State University. ORCA continues to be used as the "mode engine" for the Range-Dependent Active (RDA) model, an adiabatic-mode modeling tool developed by ARL:UT to provide TL and active sonar predictions in real-world environments.

RELATED PROJECTS

None.

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PUBLICATIONS

- E. K. Westwood and R. A. Koch, "Elimination of branch cuts from the normal mode solution using gradient halfspaces," scheduled to appear in the October or November issue of *J. Acoust. Soc. Am.*

Geoacoustic Inversion Using Vertical Line Array Data

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LONG-TERM GOAL

The long-term goal of this work is to develop a method to extract depth-dependent normal modes and to invert for the acoustic parameters of the ocean and ocean bottom using acoustic data measured on a vertical line array. Funding from this grant was also used to improve, maintain, and distribute a state-of-the-art acoustic normal mode model.

OBJECTIVES

The objectives of the FY00 work were to apply the mode extraction and geoacoustic inversion techniques developed in previous years under ONR funding to measured data and evaluate the strengths and limitations of the methods.

APPROACH

The technical approach for the geoacoustic inversion method being investigated is (1) to use measured data on a vertical line array (VLA) to extract the depth-dependent mode functions of the environment, and (2) to invert for the environmental parameters by using a non-linear least squares technique for finding the best match between extracted and modeled mode functions. The approach for evaluating the usefulness of the method is to apply the method to the ACT-II data measured in the Hudson Canyon area. This work was carried out by Tracianne Neilsen as her Ph.D. dissertation topic in the Physics Department at the University of Texas at Austin, under the supervision of Evan Westwood. A more detailed description of the technical approach is given below.

The required experimental set-up for the mode extraction method consists of a source of opportunity moving in the vicinity of a VLA. The time-dependent, single-frequency pressure field measured on the VLA may be viewed as a matrix of pressures versus receiver depth and source-receiver range. A singular value decomposition (SVD) is performed on the pressure matrix. Under certain conditions, it may be shown, using the standard normal mode expression for the pressure field, that the resulting eigenvectors correspond to the depth-dependent normal mode functions of the waveguide. We refer to this procedure as mode extraction.

The experimental requirements for the mode extraction to work well are that the water column must be sampled sufficiently well by the receivers of the VLA and that the source must cover a sufficiently large range extent. These requirements allow the pressure matrix to be written as the product of three matrices that have the same properties as the matrices returned by the SVD. An SVD of the pressure matrix yields singular vectors and singular values. The singular vectors span the space of the pressure matrix and, if the mode extraction is successful, correspond to the depth-dependent mode functions. The resulting singular values, which are returned from largest to smallest, are proportional to the modal source excitations. Thus, the source depth chiefly determines the order in which the normal modes will be extracted. The main concern with the singular values is that when neighboring singular values are nearly equal, their corresponding singular vectors are not unique. In this case, the correct mode functions are linear combinations of the eigenvectors, which preserve the orthonormality condition. Modes having close singular values must be ignored in the inversion. Once the mode functions have been extracted from the data, they may be used to invert for the parameters of the acoustic waveguide. The inversion method we used is based on Levenberg-Marquardt nonlinear optimization. In this method, the environmental parameters are adjusted to minimize the squared difference between the extracted mode functions and the corresponding mode functions modeled by the ORCA normal mode model.¹ Multiple frequencies are used in order to increase the amount of information contained in the inversion.

WORK COMPLETED

Software that performs the mode extraction and geoacoustic inversion was tested using data measured during the ACT-II experiment. The methods and results are described in detail in the Ph.D. dissertation completed by Tracianne Neilsen. Results have been presented to the underwater acoustics community at three Acoustical Society of America meetings.^{2,3,4}

RESULTS

The mode extraction technique was applied to data measured during the ACT-II experiment. Figure 1 shows the geometry of the ACT-II VLA, one of the measured sound speed profiles, the bottom profile

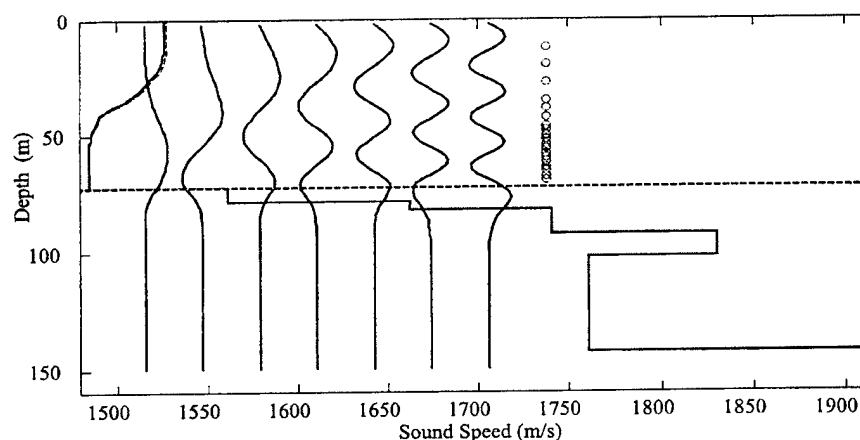


Figure 1. VLA elements (green circles), sound speed profile (red), nominal bottom profile⁵ (red), and mode functions (blue) for the ACT-II experiment.

derived in the area from Ref. 5, and the mode functions for the waveguide at 150 Hz. The sparseness of the VLA in the upper part of the water column is not ideal, but simulations indicated that low-order modes could be extracted fairly well.

Mode extraction from the ACT-II data was performed for various range extents for six tones from 100–500 Hz. The mode extraction initially worked better for the lower frequencies (100, 150 and 200 Hz) because the SVD eigenvalues were well separated and because the SNR was high. To obtain good mode extraction results at the higher frequencies (300, 400, and 500 Hz), a larger integration time was used to increase the SNR. Extracted modes at (a) 150 and (b) 300 Hz for a range-independent leg of the TL2/93 run are shown in Fig. 2. The range extent traversed by the source was approximately of 6–14 km. Despite the sparseness of the VLA, the mode extractions appear to have worked very well. The downward-refracting sound speed profile present during the measurements is reflected by the shapes of the extracted mode functions, particularly those of low order. The order of the extracted modes is caused primarily by the modal source excitations at the source depth of 36 m.

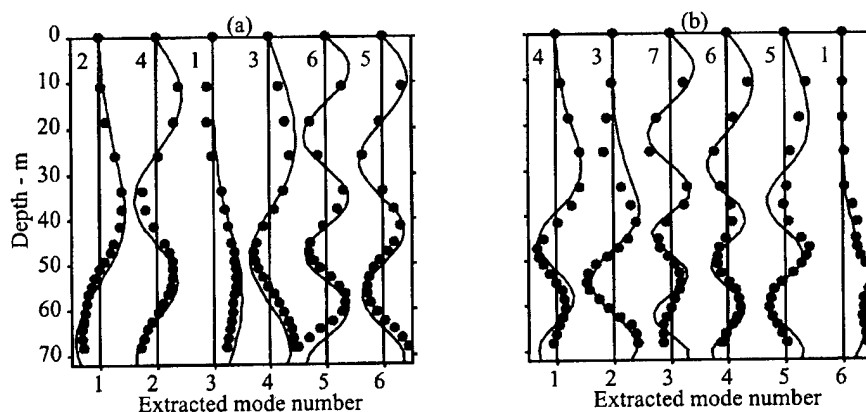


Figure 2. *Extracted modes (circles) at (a) 150 Hz and (b) 300 Hz from a range-dependent leg of ACT-II experiment using a range extent of 6–14 km. The continuous lines are modes modeled by ORCA for the nominal environment illustrated in Fig. 1. The numbers near the top of the modes indicate the modeled mode number.*

Next, the idea reported in Refs. 6 and 7 that the mode extraction can be performed using a broad distribution of uncorrelated sources was tested using ambient ocean noise recorded during the ACT-II experiment. Specifically, we used 10 minutes of data recorded when the ship was at least 22 km from the VLA and the source for the tones was off. A shorter integration time was used such that the data were averaged over 6.4 Hz frequency bands. The results of mode extraction at (a) 175 and (b) 325 Hz are shown in Fig. 3. The order of the extracted modes gives an approximate value for the effective source depth of the ambient noise. The primary extracted modes all have larger amplitudes at depths less than 10 m than the secondary extracted modes. Thus, the approximate source depth for the ambient noise obtained from the mode extraction is 10 m or less. A shallow depth for the ambient noise is logical because the data was most likely associated with ship or surface noise.

Finally, the mode functions extracted from the six tones were used to invert for the water depth and the geoacoustic parameters of the bottom. The bottom was assumed to consist of two layers and a lower half-space; the layer parameters allowed to vary were the thicknesses, the compressional-wave sound

speeds, the attenuations, and the densities. Inversion runs were performed using modes extracted from various range extents and using different initial environments. The mean and standard deviations of the results of these inversion runs are summarized in Table 1. The result for the water depth agrees well with the historic values found in Refs. 5, 8, and 9. The presence of a thin top sediment layer and the sound speed at the top of that layer also agree with the historic values. The extracted modes are not sensitive enough to changes in density, attenuation or to any parameters in the second layer to give reasonable estimates of those values.

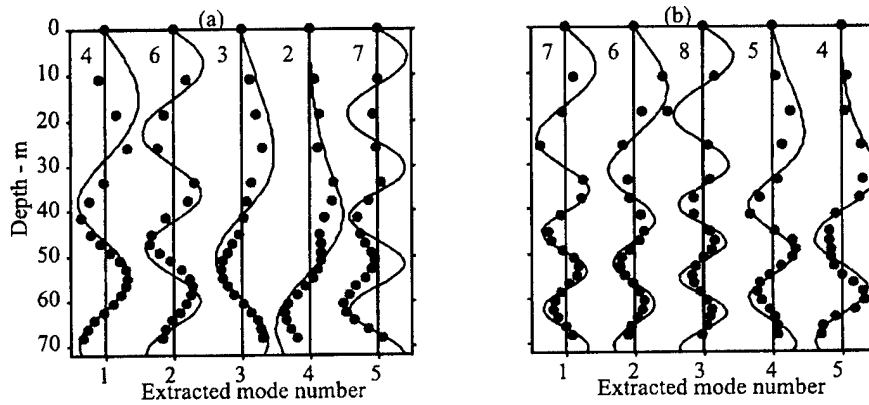


Figure 3. *Extracted modes (circles) at (a) 175 Hz from ambient noise recorded during the ACT-II experiment. The continuous lines are modes modeled by ORCA for the nominal environment illustrated in Fig. 1. The numbers near the top of the modes indicate the modeled mode number.*

Table 1: Summary of inversion results using data-extracted modes and historic values^{5,8,9}

Parameter	Mean	σ	Historic	Units
Water depth	72.35	0.6	71.6 - 73	m
Layer 1: h	5.5	3.3	5	m
c_p (top)	1565	80	1561	m/s
ρ	2.6	0.88	1.86	g/cm^3
α	0.10	0.15	0.053	dB/m-kHz
c_p (bottom)	1675	237	1561	m/s
Layer 2: h	30	20	5	m
c_p (top)	1964	263	1661	m/s
ρ	1.14	0.88	1.96	g/cm^3
α	0.47	0.26	0.082	dB/m-kHz
c_p (bottom)	1984	258	1661	m/s

In summary, the mode extraction technique works well if the VLA samples the water column well and the sources either cover a sufficient range extent or are uncorrelated, as in the case of ambient noise. The acoustic source need not be controlled: its depth, the phase of its tonals, and its precise track do not need to be known. When applied to the ACT-II data set, the mode extraction appears to have worked very well, despite the relative sparseness of the array near the top of the water column. When

the extracted modes were used to invert for the bottom, the results were encouraging, but the depth to which the parameter values could be reliably obtained was less than 10 m. Since the mode functions decay rapidly with depth in the bottom, little information about the bottom below a few wavelengths is available. Although more information would be desirable, the field from sources beyond the near field is only dependent on the parameters near the surface. Unfortunately, the mode functions are not very sensitive to attenuation, even in the top sediment layer. The extracted depth-dependent mode functions are also useful for determining water depth and the sound speed profile in the water column, but in practice these values can usually be measured by other means.

IMPACT/APPLICATIONS

The technique for mode extraction and inversion is applicable to vertical line arrays that span and sample the water column sufficiently well to account for the dominant modes of propagation.

TRANSITIONS

No transitions have occurred for the geoacoustic inversion method. We continue to make the ORCA normal mode model available to the community and to provide support to users when needed. We have been informed of use of the model at the following institutions: NRaD, MPL; NAWC, U. of Hawaii; SACLANT; NRL SSC; U. of Victoria; MIT/WHOI; University of Bochum (Germany); and Pennsylvania State University. ORCA continues to be used as the "mode engine" for the Range-Dependent Active (RDA) model, an adiabatic-mode modeling tool developed by ARL:UT to provide TL and active sonar predictions in real-world environments.

RELATED PROJECTS

None.

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